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Surface Temperature Measurements on Burning Wood Specimens in the Cone Calorimeter and the Effect of Grain Orientation

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Surface temperatures were measured on dry Douglas fir sapwood specimens during Cone Calorimeter tests using thermocouples and an infra-red pyrometer. Good agreement between the thermocouples and the pyrometer was obtained when (1) the emissivity was assumed to be 1.0 and (2) the thermocouples were in good contact with the surface and were not located in the proximity of a fissure. The major fissures were normal to the grain of the wood and the volatiles vented through the fissures. Char oxidation in the region between the vertical fissures resulted in higher surface temperatures.

INTRODUCTION

The Cone Calorimeter has become an ASTM and an ISO standard [1,2] for measuring the heat release rate of materials. While this instrument can measure the heat release rate as a function of incident flux, fire-growth models require information on the heat release rate as a function of the net heat flux into the surface. This net heat flux can be calculated if the surface temperature can be measured during the test. This paper demonstrates that it is possible to routinely measure the surface temperature of vertical specimens of wood in the Cone Calorimeter using an infra-red pyrometer.

EXPERIMENTAL METHODS

All the specimens were cut from the clear sapwood region of one Douglas fir board. They were 36 mm thick and 100 mm square as required for testing in the Cone Calorimeter. Prior to testing, the specimens were dried at 105°C to a constant mass. They were tested in the vertical position with the rear surface in contact with a 10 mm thick calcium silicate board. The edges and the rear surface of the specimens were covered with aluminum foil. The grain orientation was horizontal in all of the tests except where specifically indicated below. Tests were run at incident fluxes of 20, 35, 65 and 80 $kW\,m^{-2}$.

The surface temperature was measured with 0.127 mm diameter chromel-alumel thermocouples and with an infra-red pyrometer. The role of the thermocouple measurements was to calibrate the pyrometer which could then be used alone for routine testing.

A technique was devised to measure the surface temperature using the fine thermocouples. Two small-diameter holes were drilled through the specimen about 10 mm apart along a horizontal line. Teflon tubes were inserted into the holes. The thermocouple wires were then run through the tubes so that the hot junction of the thermocouple was located on the exposed side of the specimen midway between the holes. The wires ran horizontally between the holes and were held tight against the surface to virtually eliminate temperature gradients which would conduct heat toward or away from the junction. The wires passed through the calcium-silicate backing board and were held in tension with rubber bands attached to an aluminum frame. This arrangement kept the thermocouple junctions in contact with the surface during the duration of the test so that they followed the regression of the surface caused by char shrinkage and oxidation. The Teflon tubes served to prevent the pyrolysis products of the wood from condensing on the wires in the cooler regions of the holes. During preliminary tests without these tubes the wires were cemented in place by the condensate and would not move freely. The fire-exposed projections of the tubes were continuously burned off during the test. Thus the ends remained flush with the surface as it regressed and did not interfere with the contact between the wires and the surface.

It is extremely important to keep the thermocouples on the surface to prevent the influence of the steep temperature gradients normal to the surface in both directions (toward the flame or into the char). It was necessary to find the right force to be applied by the rubber bands so that the hot junction would neither be pulled into the char (too high a tension) nor lose contact with the exposed surface (too low a tension).

Usually three thermocouples were installed on each specimen: one at the center and the other two about 15–20 mm below and above it. In some cases the thermocouples junctions were all located along a horizontal line to reduce the risk of having all three over a vertical fissure. The major fissures developed normal to the grain orientation which was horizontal in most of the tests. The fissures were the most disturbing factor in these measurements. It is impossible to predict where they will occur. The thermocouples were observed periodically to see if there were any problems which would invalidate the measurements. Because of the care required in their

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installation and the problem of the fissures, thermocouples are not recommended for routine surface temperature measurements.

The infra-red pyrometer[a] was a major improvement in measuring the surface temperature. With the pyrometer 750 mm from the surface the target area is a circle approximately 15 mm in diameter which can be moved during the test to avoid the fissures. Its wavelength band is 8–12 μm, so that the emission from water vapor (5.6–8.0 μm) and CO_2 (4.2–4.4 μm) cannot be 'seen' and the measurements are not degraded significantly by atmospheric absorption. The wavelength band of the pyrometer is also beyond that of the soot emission from the flame. The temperature range of the pyrometer is from 38°C to 1093°C, which is sufficient to follow the surface temperature from ambient to the highest value that can be reached in the Cone Calorimeter.

DESCRIPTION OF THE BURNING PROCESS

Within 10–30 s after ignition, two or three vertical fissures began to develop. They were always oriented perpendicular to the grain direction and ran across the whole height of the specimen when the grain was horizontal or the whole width if it was vertical. The width of the fissures varied from 2 to 15 mm by the end of the test and increased with increasing incident heat flux. Also, a few fine fissures parallel to the grain appeared towards the end of a test. At the beginning of each test, flames covered the entire surface of the specimen. As the fissures developed, the flames tended to emerge from the fissures only. This was because the volatile pyrolysis products take the path of least resistance and travel internally along the grain and vent into the fissures. When the fissures were vertical the flames traveled upward along them. Later in the test as the fissures broadened, the flames were contained within them. Since the areas between the fissures were not covered by flames, ambient oxygen diffused to the surface and oxidized the char. The flames were more intense toward the top of the specimen because the mass flow of volatiles along the fissures increased with height due to the cumulative contributions along the way. Toward the end of the pyrolysis process the mass flow near the bottom was not sufficient to support a flame so the lower boundaries of the flaming regions moved slowly upward until the flames were extinguished at the top.

Until the flaming was complete, the width of the specimen was close to its initial value. The height of the specimen was greatly reduced due to char shrinkage whereas the shrinkage along the grain resulted in fissure formation. At the end of the pyrolysis process, i.e. when the fissures reached the rear side of the sample, they closed up and the width of the remaining sample shrank by about 10 mm on each side. At this point only the char was left. All the flames disappeared, but the char oxidation continued. At the end of the flaming period it was observed that much of the char had already been consumed by oxidation at the lower part of the sample. When the grain was vertical so that the fissures were horizontal, the volatiles left the fissures and covered the surface above them with flames. Thus all the area of the specimen above the bottom fissure was covered with a flame sheet during the intense burning period and char oxidation could not occur. The impact of this on the surface temperature will be discussed below.

TEMPERATURE MEASUREMENTS

The temperature recorded by the pyrometer was compared with that measured by the thermocouples in order to determine the emissivity of a Douglas fir specimen, before and after ignition. A specimen, equipped with three thermocouples, as described above, was exposed to an incident flux of 20 kW m^{-2} and was not ignited. Only small fissures occurred during this test, so the thermocouple readings were not affected. After setting the emissivity to a value of 1, very good agreement was found between the pyrometer and the thermocouple readings as shown in Fig. 1. This means that the Douglas fir specimens were effectively 'black' in the wavelength band between 8 and 12 μms even before the temperature was elevated sufficiently to initiate thermal degradation. The abrupt change in the pyrometer reading at 700 s was due to the intentional movement of the target area away from a fissure. The sharp increase in temperature at the end of the test, indicated by both the pyrometer and the thermocouples, was due to an accelerated rate of char oxidation. The pyrometer and thermocouple measurements on a specimen with a horizontal grain orientation are shown in Fig. 2 for an exposure of 65 kW m^{-2}. The temperature recorded by one of the thermocouples followed that of the pyrometer very closely after 10 min. The temperature reading will be lower than that of the pyrometer if the thermocouple is pulled into the char due to too much tension. This difference would diminish with time as the temperature gradient in the char drops off and the depth of the thermocouple decreases due to char oxidation. This could be the reason that the thermocouple did not follow the pyrometer during the early part of the test. The other two thermocouples had reduced temperatures since they were located close to a fissure. They eventually broke during the course of the test. The pyrometer readings should be accurate based on the results in Fig. 1, except in the case where a target area includes a fissure. The

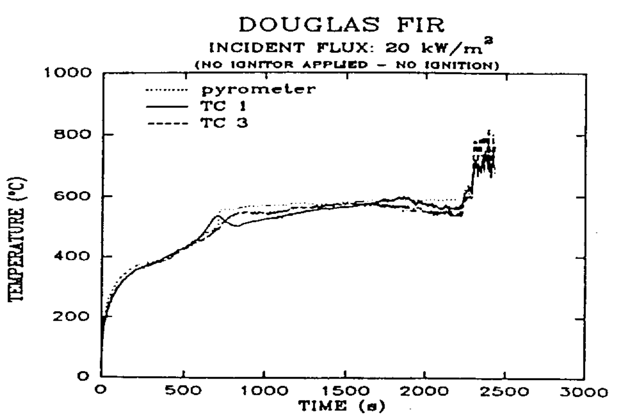

Figure 1. Comparison of pyrometer and thermocouple measurements on an unignited specimen.

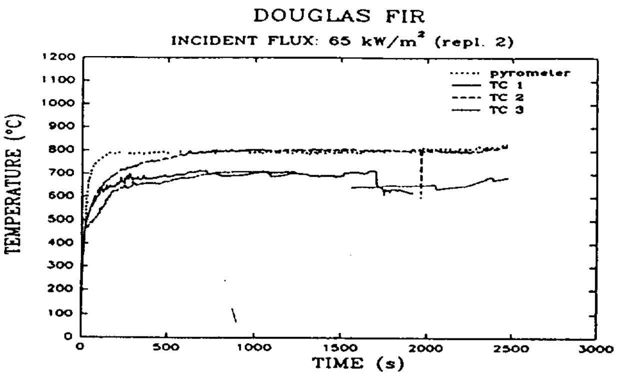

Figure 2. Comparison of pyrometer and thermocouple measurements on an ignited specimen.

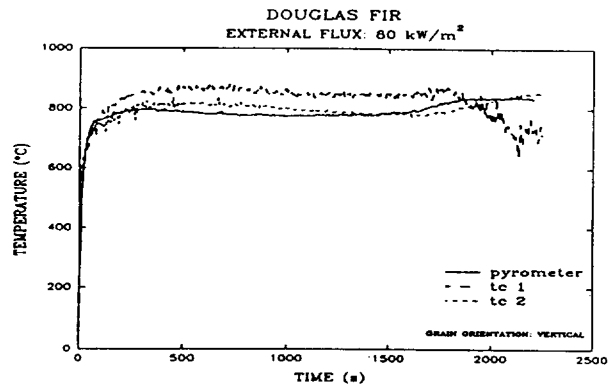

Figure 4. Pyrometer and thermocouple measurements on a specimen with vertical grain orientation.

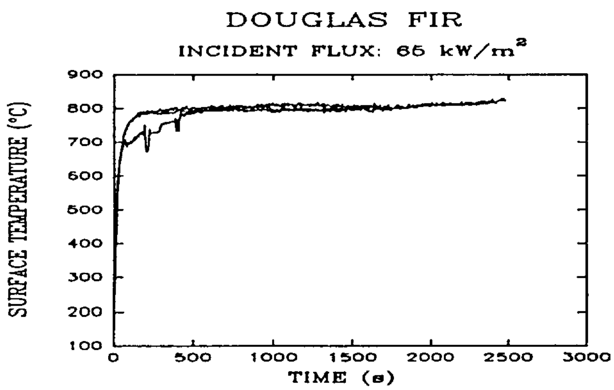

Figure 3. Replicate measurements with a pyrometer on an ignited specimen.

pyrometer target area can be moved. The thermocouple cannot. After heat conduction into the interior becomes small, the pyrometer reading is consistent with temperature calculations based on incident flux, char oxidation and radiative and convective heat losses.

The surface temperature history measured by the pyrometer on three replicate tests at 65 kW m^{-2} is shown in Fig. 3. The results are quite reproducible except in one case where the target area was too close to a fissure and was finally moved away from it after 8 min.

Figure 4 shows the temperatures measured with the pyrometer and the thermocouples for a specimen whose grain direction was vertical. The exposure flux was 80 kW m^{-2}. A much larger fraction of the specimen surface was covered by flames as the volatiles flowed upward out of the horizontal fissures. Only the surface below the lowest fissure was not covered by flames. The thermocouple whose recorded temperature was significantly higher than that of the pyrometer did not follow the regression of the surface but was located in the gas phase closer to the flame. The temperature of this thermocouple dropped after 30 min when the flame went out. The temperature, measured by the pyrometer and the thermocouple contacting the surface, increased as char oxidation began. The surface reached a temperature 60°C above that which it had when it was covered with flame.

The rate of char oxidation at the temperatures attained in these experiments is primarily controlled by the rate of oxygen diffusion to the surface.[3] The rate of diffusion of oxygen to the flame sheet is essentially the same as it is to the oxidizing surface in the absence of the flame sheet. The heat release per unit mass of oxygen consumed is the same for either case.[4] Since the efficiency of the heat transfer to the surface is greater for char oxidation than for flaming combustion which takes place away from the surface, the temperatures are observed to be higher for those surfaces undergoing char oxidation.

SUMMARY AND CONCLUSIONS

The major fissures were normal to the grain of the wood and the pyrolysis products traveled laterally to the fissures and vented there. Consequently, for specimens whose grain was horizontal, the flames traveled up the vertical fissures leaving large areas of the surface between them subject to char oxidation. For vertical grain orientations the fissures were horizontal and the flames covered the surface between the fissures thus excluding it from oxygen attack. The temperatures were lower for the flame-covered surfaces because the heat fluxes from the flame are less than those produced by char oxidation.

Good agreement between the thermocouples and the pyrometer was obtained when (1) the emissivity was assumed to be 1.0 in the wavelength band of the pyrometer and (2) the thermocouples were in good contact with the surface and not located in the proximity of a fissure. An infra-red pyrometer in the wavelength band between 8 and 12 μm is ideally suited for measuring the surface temperature of burning wood specimens exposed in the vertical orientation in the Cone Calorimeter on a routine basis.

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NOTES

[a] A Maxline infra-red pyrometer, with an M402 Sensor, made by Ircon, Inc. in Niles, Illinois, was used on this project. This does not constitute an endorsement by the National Institute of Standards and Technology.

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